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Millimetre observations of Pleiades stars: a lack of solar-analogue planetesimal discs at 100 Myr?

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ABSTRACT

Solar analogues approximately 100 Myr old may have dusty debris from collisions within evolving cometary belts, and such remnant discs might also be associated with earlier stellar-spin braking. We observed at 1.2 mm wavelength a sample of 17 fast and slow rotators, mostly single K dwarfs, in the 100 Myr Pleiades cluster. No dust was detected for individual stars or the ensemble, so there are no cold massive debris discs nor any discernible relation of such distant material to stellar spin. The net limits from these data and our earlier far-infrared results imply that the typical Pleiades G/K dwarf has a relative disc-to-star luminosity $\lesssim 2 \times 10^{-4}$. Collisional evolution models have predicted greater luminosities at the 10^8 yr epoch, for debris discs evolving out of a proto-solar nebula. This suggests that substantial primordial discs such as that of the Sun are not the norm amongst young solar analogues, or that dynamical interactions with giant planets can remove much of the comet belt by as early as 100 Myr.

Key words: circumstellar matter – planetary systems – infrared: stars.

1 INTRODUCTION

Circumstellar environments of stars in clusters a few tens of millions of years old are interesting in the study of the late stages of planet formation. The collisions of planetesimals should build up rocky terrestrial planets, and any evolving system of outer gas giants should stir up a comet belt at tens of au from the star. These perturbations increase the rate of comet collisions, generating dusty debris whose thermal emission can be detected from the mid-infrared to millimetre (e.g. Meyer et al. 2007), depending on the distance from the star and thus equilibrium temperature of the dust grains. Recent *Spitzer* 24–70 μm observations of Sun-like field stars in the age bracket 20–50 Myr show such dust excesses with 10–20 per cent frequency (Hillenbrand et al. 2008; Meyer et al. 2008), with slightly higher 24 μm incidence of ≈30–40 per cent in clusters (Siegler et al. 2007).

At 100 Myr, the Pleiades has debris detections for only around 10 per cent of the FGK dwarfs observed at 24–90 μm with *Spitzer* and *ISO* (Spangler et al. 2001; Stauffer et al. 2005; Gorlova et al. 2006). Millimetre dust emission should be particularly bright at this time for stars with cold comet belts, whereas the far-infrared fluxes may be declining as they trace grains nearer the star, where the main planetary evolution could have taken place earlier (Kenyon & Bromley 2005). In spite of its relative proximity at approximately 133 pc (Soderblom et al. 2005), this cluster has not been targeted with millimetre observations since the pioneering work of Zuckerman & Becklin (1993), who obtained a 3σ upper limit of 6 mJy at 0.8 mm for six FGK stars. Deeper millimetre observations are promising for this epoch, as, for example Najita & Williams (2005) found 2/6 of Sun-like field stars of ≈60–180 Myr age to have substantial cool debris detectable at 0.85 mm.

We have therefore made new sensitive observations with a millimetre bolometer camera at the IRAM 30-m, targeting 17 Pleiades stars and going an order of magnitude deeper in flux sensitivity than Zuckerman & Becklin (1993). An additional goal of the observations was to test if massive remnant discs are relic evidence of primordial discs when these stars were in the T Tauri phase at a few million years. At this stage, magnetic fields could link the young star to the inner edge of the accretion disc, providing a mechanism to transfer angular momentum outwards, and so brake stellar spin-up as the star contracts towards the main sequence (Collier Cameron, Campbell & Quaintrell 1995; Armitage & Clarke 1996). Since much of the primordial disc mass would have been at large radii (e.g. Wyatt, Clarke & Greaves 2007a), massive cold remnant discs could be associated with slow-spinning stars (Bouvier 2008), while those that lost their discs early on would have little debris and fast rotation.

We therefore selected nine of the Pleiades stars with the longest periods (> 140 h) and a control group of eight stars with the shortest periods (< 10 h). The targets (Table 1) are mainly K dwarfs as these

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Table 1. Parameters for the Pleiades stars (HII 3030 is an uncertain member). Spectral types from SIMBAD are given where available, along with periods and $v \sin i$ measurements from the literature. The 1.2 mm flux densities are the measured mean signal and 1σ error after N(obs) 20-min observations; also listed are co-added mean fluxes of the two data sets.

Target HII:	Period (h)	$v \sin i$ (km s^{-1})	Spectral type	F(1.2 mm) (mJy)	N(obs)
		Slow rotators			
34	157	6.6	G8	-0.5 ± 0.9	1
879	177	6.4	G5	$+1.7 \pm 1.0$	1
883	173	3.8	–	$+0.4 \pm 1.0$	1
1124	145	4.5	K3	-0.4 ± 0.8	1
1332	199	5.3	K4	-0.5 ± 1.1	1
2284	242	3.6	–	-0.2 ± 1.0	1
2341	197	3.5	G4	-0.7 ± 1.0	1
2548	180	5.7	K7	-0.2 ± 0.5	3
3030	178	<9	K	-0.4 ± 0.7	1
(all slow:)				-0.4 ± 0.3	
		Fast rotators			
324	9.9	73	—	$+0.7 \pm 0.8$	1
335	6.4	73	K5	$+0.1 \pm 0.9$	1
347	9.7	75	K7	-1.0 ± 0.9	1
559	8.3	65	—	-0.5 ± 1.0	1
686	9.5	64	K7	$+0.7 \pm 0.4$	7
1883	5.7	140	K2	-0.1 ± 1.0	1
2208	9.9	73	K6	$+0.6 \pm 0.6$	2
2927	6.3	95	K4	-0.6 ± 0.6	2
(all fast:)				-0.1 ± 0.2	

have the most pronounced period divergence at the Pleiades age, and they are nearly all single stars (Fig. 1).

2 OBSERVATIONS

The data were taken with the MAMBO-2 1.2 mm camera in 2006 February/March, and reduced with the MOPSIC package written by R. Zylka.[1] The sky opacities were approximately 0.1–0.2, and standard calibrations obtained over the winter 2005/6 observation pool were applied; Mars was used as the flux calibrator during the run. An on–off photometry integration of 20 min was made on each star using the most sensitive bolometer, with repeats for some sources observed at lower elevations or in poorer conditions.

Nebulosity in the Pleiades could contribute extended millimetre flux, but this should be largely removed by sky chopping apart from any structure on small scales. (The beam size is 11 arcsec and a 35 arcsec chop throw was used.) The mean extinction is $A_V = 0.12$ (Stauffer et al. 2003) and only HII 686 is identified as having extra reddening in the optical. This object was observed to greater depth to follow up an initially positive signal but no dust of any origin was confirmed. No circumstellar discs were detected among the 17 stars, and of the three signals lying beyond $\pm 1\sigma$, all are for stars lying within regions of moderate-to-high nebulosity (e.g. in the *IRAS* 12 μm map of the Pleiades). Final rms-noise values at 1.2 mm are approximately 1 mJy per target and are listed in Table 1.

3 RESULTS AND DISCUSSION

Given the 3σ limits of approximately 3 mJy, the survey would have detected dust-disc masses of around 1 $M_\oplus$, assuming a millimetre opacity ≈ 1 cm^2 g^{-1} and grain temperatures of a few tens of

[1] http://www.iram.es/IRAMES/mainWiki/CookbookMopsic

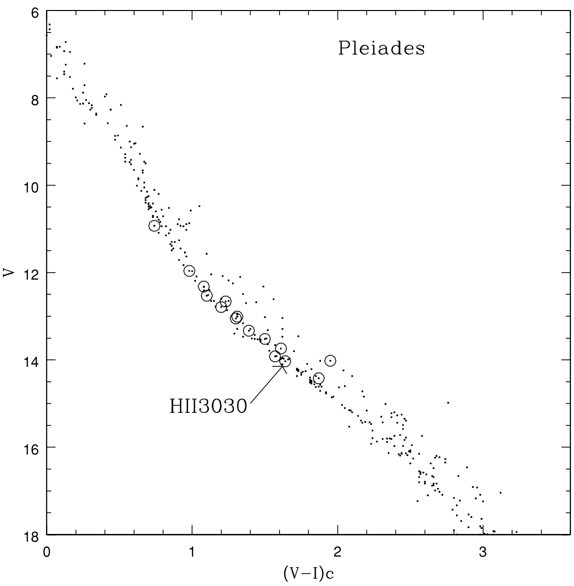

Figure 1. Colour–magnitude diagram for the Pleiades, showing that most of the target stars (circles) lie on the main sequence and so are single objects associated with the cluster. The point above the main sequence is HII 347 and is probably a binary of two fast rotators (broad lines only are seen); HII 2284 is also a probable binary (Raboud & Mermilliod 1998, SB1). HII 3030 is an uncertain Pleiades member with a discrepant radial velocity (Queloz et al. 1998).

K (e.g. Najita & Williams 2005). No such massive cold discs are present in the 17-star sample, and with no distinguishing characteristics of the fast and slow rotator fluxes, so the spin-braking idea cannot be tested. Similar dust-mass limits have been obtained for various stars of comparable age observed at 0.35–3 mm (Carpenter et al. 2005).

A deeper limit was obtained for the ensemble of stars by co-adding the data for all 17 objects as if they were one sky position, giving a net signal of $F_d = -0.26 \pm 0.18$ mJy. The 3σ limit for the mean per-star disc flux is therefore 0.54 mJy. For the average 1.2 mm photospheric flux of 5×10^{-4} mJy, the upper limit on the average excess ratio $R_{1200} = F_d/F_*$ is therefore approximately 1000. More accurately, i.e. taking into account the non-equal photospheres, the individual upper limits on R_{1200} can be added in quadrature to give a net value $R_{1200} \leq 1600$. The same calculation was also made for 19 mainly G-type stars in the Pleiades observed by Stauffer et al. (2005) at 70 μm with *Spitzer*. In this case, the ensemble-R_{70} is $\leq$23 with 3σ confidence – the value is lower predominantly because stellar photospheres are much brighter in the far-infrared than in the millimetre.

The flux ratios may be converted into the relative dust luminosity via

$$L_{\rm dust}/L_* = \frac{e^{h\nu/KT_{\rm dust}} - 1}{e^{h\nu/KT_{\rm eff}} - 1} (T_{\rm dust}/T_{\rm eff})^4 F_{\rm dust}/F_* \quad (1)$$

(Beichman et al. 2006). This quantity is sensitive to the assumed dust temperatures, which are generally observed to be tens of K for exo-Kuiper belt analogues. In thermal equilibrium (e.g. Wyatt et al. 2007b) with a 0.25 $L_\odot$ mid-K star, blackbody grains have a temperature of only 20 K at 100 au. The dust would be slightly warmer for smaller orbits (e.g. tens of au), or for solar-luminosity G dwarfs, or for grain materials with grey body properties (in particular, small grains emit less efficiently than blackbodies at wavelengths shortwards of about 100 μm). Since the millimetre data are most sensitive

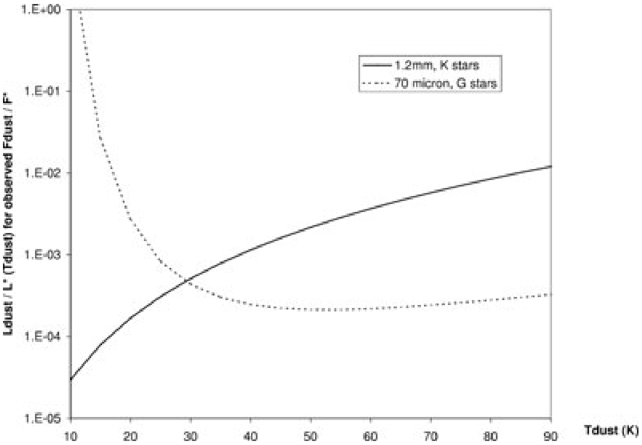

Figure 2. Sensitivity of the minimum detectable dust-to-star luminosity ratio to assumed dust temperature. From the far-infrared and millimetre observations considered together, only the luminosity regime below both curves would escape detection for the stellar ensembles.

to cold belts, we consider 20 K blackbody dust[2] around K stars of $T_{\rm eff} \approx 4700$ K, for which $R_{1200} \leq 1600$ corresponds to $L_{\rm dust}/L_* \leq 2 \times 10^{-4}$. For the *Spitzer* sample of G dwarfs taken to have $T_{\rm eff} \approx 5800$ K, the limit $R_{70} \leq 23$ translates to $L_{\rm dust}/L_* \leq 3 \times 10^{-3}$ at 20 K; however, this limit should probably be lower taking into account that the far-infrared surveys are sensitive mainly to warmer dust populations. For example, for 50 K blackbody dust orbiting at around 30 au, the $L_{\rm dust}/L_*$ limit would again be $\leq 2 \times 10^{-4}$. In actuality, a range of dust temperatures are likely to be present, for grains of different sizes, compositions and orbital distances, and the combination of far-infrared and millimetre data has good sensitivity across all likely temperatures for comet belts (Fig. 2).

3.1 Comparison to models

Several recent models have investigated the collisional evolution of dusty debris. Wyatt et al. (2007b) and Löhne, Krivov & Rodmann (2008) follow the fragmentation processes in cometary belts containing up to ~50 km objects, while Kenyon & Bromley (2008) include the dynamical stirring caused by the growth of planet-sized bodies (radii up to ≈1750 km). These studies all include the 10^8 yr epoch and predict $L_{\rm dust}/L_*$, and/or $F_{\rm dust}/F_*$ at relevant wavelengths, allowing direct comparison to the data.

Our millimetre and far-infrared surveys were planned to address the question of whether young solar analogues typically possess comet populations like the early Kuiper belt. This had a mass in planetesimals estimated at 10–30 $M_\oplus$ between 40 and 50 au (Charnoz & Morbidelli 2007), although much of this material was later lost. Here, we adopt model results for more massive discs in order to maintain similar surface densities of bodies, as the range of radii over which the planetesimals are spread is greater in the models. For example, with a surface density profile declining as $r^{-3/2}$ (Kenyon & Bromley 2008), the enclosed mass scales as $(\sqrt{r_{\rm outer}} - \sqrt{r_{\rm inner}})$, and hence the 40–50 au radius zone includes only one-sixth of the material in a 30–100 au-wide belt.

The specific model runs that are most relevant here are as follows. (The dynamical times are 20 per cent longer for a 0.7 $M_\odot$ K dwarf than for a solar-mass star, but we neglect this small correction to the dust evolutionary tracks of the models and use 100 Myr predictions throughout.)

(i) Wyatt et al. (2007b, fig. 5) have 100 $M_\oplus$ in planetesimals in a 100 au outer-radius disc around an A-type star. Here, we increase their $L_{\rm dust}/L_*$ by $1/\sqrt{M_*}$ (using their equation 14) to correct for our three to four times lower stellar masses.

(ii) Löhne et al. (2008, fig. 11) have 30 $M_\oplus$ of bodies in a 30 au disc around a solar-mass star. Adjustments for larger and more massive discs would cancel in this model, e.g. a doubling of $L_{\rm dust}/L_*$ for a 100 $M_\oplus$ disc could be cancelled by a factor of 2 decrease for a 100 au radius.

(iii) Kenyon & Bromley (2008, figs 14 and 16) have 100 $M_\oplus$ of bodies in a 150 au disc around a solar-mass star. The dust luminosities are adjusted downwards here by 40 per cent, as these authors note such a (flux) decrease for a disc outer radius of only 70 au.

Then, at the Pleiades age of 100 Myr and for our example discs of around 100 au and 100 $M_\oplus$, the first two (unstirred) models predict $L_{\rm dust}/L_*$ of ≈2.5–3 × 10^{-4}. The model stirred by the formation of small planets predicts some enhancement of dust emission over a broad epoch around this time, with a higher $L_{\rm dust}/L_* \approx 10^{-3}$. For comparison, our observed ensemble limits are $\lesssim 2 \times 10^{-4}$, assuming millimetre and far-infrared emission trace roughly 20 and 50 K dust, respectively. Thus, the model comparisons suggest that these Pleiades G and K stars can *not* generally possess such a 100 au, 100 $M_\oplus$ disc.

This conclusion is reasonably robust in spite of the uncertain dust temperatures. Fig. 2 shows the inferred lower limits to detectable luminosity ratios (equation 1) for the observed $F_{\rm dust}/F_*$ ensemble limits, as a function of temperature. The model predictions of $L_{\rm dust}/L_*$ of a few 10^{-4} are generally detectable in one of the two wavelength regimes observed, for any temperature – the worst case is 30 K dust where we could only detect $L_{\rm dust}/L_* > 5 \times 10^{-4}$. Strictly, our conversion of $F_{\rm dust}/F_*$ to $L_{\rm dust}/L_*$ only applies if all the dust has a single temperature, i.e. narrow rings of identical grains, whereas in the models the regions of brightest dust can be broad. Narrow rings may be a better analogue to the Kuiper belt and would be less luminous than broader discs (Wyatt et al. 2007b), but as noted by Kalas et al. (2006) a mixture of broad and narrow belts exists among Sun-like stars. Kenyon & Bromley (2008) show that at 70 μm, near the blackbody peak of the emission for most grains, the excess flux and fractional luminosity are almost linearly related, but in the millimetre, in the Rayleigh–Jeans tail, the excess flux depends strongly on the disc outer radius. However, the correction made above for disc size [which should strictly be to flux as plotted by Kenyon & Bromley (2008), not luminosity] is small for the regime of disc size and age considered here. Finally, as noted by Kenyon & Bromley (2008), model details can affect $F_{\rm dust}/F_*$: for example, the survival of smaller grains against radiative blowout for lower-mass stars can boost the dust fluxes by factors of a few, as can changing the adopted emissivities.

Modulo these parameters that we cannot control for in the data, if *each* Pleiades star has a comet belt of surface density similar to that in the early solar nebula, the net dust fluxes of cool or warm debris are expected to have been detected. In all the models, the 100 Myr epoch is ideal for observing such debris, being near peak luminosity and/or highest flux in at least one of the two wavelength regimes.

[2] Dust this cold is so far not confirmed in many systems, but inferred for large discs around Sun-like stars [see e.g. the 17 K grain population for q^1 Eri discussed by Liseau et al. (2008)].

3.2 Relation to other Sun-like stars

A number of debris discs are known among Sun-like stars around 100 Myr old [see Wyatt (2008, fig. 10) for a summary]. These detected examples have $F_{\rm dust}/F_*$ at 70 μm of approximately 12 up to 300, whereas our ensemble Pleiades limit is ≤23. This places the typical Pleiades G dwarf as less dusty than 70 per cent of the 10 known examples of debris discs of similar age. The known disc systems are, however, a skewed population, as far-infrared excesses are difficult to detect for the distances to young stellar associations, and they probably represent the tip of the iceberg among more than 100 stars of roughly similar age surveyed, e.g. by the Formation and Evolution of Planetary Systems (FEPS) project (Carpenter et al. 2008). One reasonable analogue to a young Solar system with an imaged debris disc is HD 139664, which is an F5 star of the order of 300 Myr old, hosting a narrow dust ring spanning 83–109 au in radius with a 70 μm excess of 18 (Beichman et al. 2006; Kalas et al. 2006). The fractional luminosity is 1.3×10^{-4}, which is consistent with the hypothesis that this is a young solar nebula analogue that has already declined in far-infrared brightness (Kenyon & Bromley 2008), and so is somewhat fainter than our net G-dwarf limit at 100 Myr of $L_{\rm dust}/L_* \lesssim 2 \times 10^{-4}$.

4 RELATION TO THE SOLAR SYSTEM

The inferred lack of approximate analogues to the early Kuiper belt among the nearly 40 Pleiades stars observed is surprising, if the Sun is thought to be a typical low-mass star and thus to have hosted an average planetesimal disc at early times. The Pleiades environment could be unrepresentative of that in which the Sun formed – although this may have taken place in a cluster or association according to the interpretation of high abundances of some radionuclides, perhaps requiring a nearby massive star to have gone supernova (e.g. Gounelle & Meiborn 2008). In general, the present-day Pleiades should be a rather *more* disc-friendly location than a dense highly populated stellar cluster. The most luminous Pleiades star is a mid-B object, and the stellar density is only ∼14 stars $\rm pc^{-3}$ at the cluster centre (Pinfield, Jameson & Hodgkin 1998) although probably higher at early times (Kroupa, Aarseth & Hurley 2001) so some discs could have been stripped earlier on, e.g., by stellar encounters.[3] Broadly, there is no special property of the Pleiades that suggests it could *not* host close analogues to the Solar system as it existed at 100 Myr.

In general, debris discs of the luminosity proposed by solar nebula models do not appear with high frequency at around 100 Myr. Our results imply that ≲5 per cent of discs have $L_{\rm dust}/L_* \gtrsim 2 \times 10^{-4}$ in the combined far-infrared and millimetre samples, and the main evidence for *any* cool high-debris systems in the Pleiades consists of two 90 μm *ISO* detections, with $L_{\rm dust}/L_*$ of a few 10^{-3} (Spangler et al. 2001). The 100 Myr epoch is thus unremarkable for luminous debris in the far-infrared or millimetre – although warm dust located in the inner few au could be more common, with mid-infrared detections towards three to five out of 20 solar-type Pleiades stars (Carpenter et al. 2005; Stauffer et al. 2005; Meyer et al. 2008) and one system known to have hot dust peaking at around 9 μm (Rhee, Song & Zuckerman 2008). This suggests that disc evolution may be slower than in models, since mid-infrared emission is predicted to be in decline by ∼100 Myr (Kenyon & Bromley 2008, fig. 18).

The low debris luminosities seen here have several possible explanations. First, the proto-solar nebula could have been atypical, and more towards the high end of the primordial-disc mass range. If a more typical Sun-like star begins with a less substantial disc, the planetesimal belt could be less massive and so the debris could be too faint to observe. This is consistent with the millimetre-wavelength survey of T Tauri star discs by Andrews & Williams (2007, fig. 8), showing incidences of only around 20 per cent of ≥50 $\rm M_\oplus$ of dust (i.e. the minimum rocky content needed to make the bodies in the Solar system). Secondly, the proto-solar nebula could have been typical, but many primordial discs could have lost material before it formed into planets and comets, and thus often be observed when already depleted. However, this is not supported by the dust masses observed over the 10^{4-7} yr era, when the incidence of dust equivalent to the minimum mass solar nebula (MMSN) is flat (Andrews & Williams 2007). Thirdly, the norm could be to form as many planetesimals as the young Sun, but to lose most of them to scattering and ejections induced by migrating giant planets, as proposed in a model explaining the late heavy bombardment of the Earth at 700 Myr (Gomes et al. 2005). In this case, the Sun would be a later-occurring example of a phenomenon required to have taken place in the Pleiades generally prior to 100 Myr, which is plausible as many such bombardment events have taken place by 300 Myr in simulations by Thommes et al. (2000a). Further, giant planets would need to be typical [cf. only ∼12 per cent inferred so far from Doppler surveys (Marcy et al. 2005) as orbiting within 20 au], and the dust masses measured in the millimetre would have to be underestimated, as Thommes, Matsumura & Rasio (2000b) find that at least a MMSN is required for giant planets to form at all.

We conclude that the low debris luminosities in the Pleiades may arise because the typical Sun-like star starts with less disc mass than possessed by the young Sun, or that dynamical interactions with giant planets may eject many comets at an earlier epoch than in the Solar system.

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[3] Gorlova et al. (2006) found four solar-type stars in the Pleiades to have 24 μm excesses, all of which fall into the majority population of low-$v \sin i$ stars – potentially this supports the model where Pleiades fast rotators are stars that lost their braking discs early on and so do not now have debris.

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